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Abstract

This paper addresses two major challenges in climate change impact analysis on water resources systems: (i) incorporation of a large range of potential climate change scenarios and (ii) quantification of related modelling uncertainties. The methodology of climate change impact modelling is developed and illustrated through application to a hydropower plant in the Swiss Alps that uses the discharge of a highly glacierised catchment. The potential climate change impacts are analysed in terms of system performance for the control period (1961–1990) and for the future period (2070–2099) under a range of climate change scenarios. The system performance is simulated through a set of four model types, including the production of regional climate change scenarios based on global-mean warming scenarios, the corresponding discharge model, the model of glacier surface evolution and the hydropower management model. The modelling uncertainties inherent in each model type are characterised and quantified separately. The overall modelling uncertainty is simulated through Monte Carlo simulations of the system behaviour for the control and the future period. The results obtained for both periods lead to the conclusion that potential climate change has a statistically significant negative impact on the system performance.

Keywords: climate change, hydrological modelling, modelling uncertainty, water resources management, hydropower, glacier surface evolution

Introduction

High mountain water resource systems are particularly sensitive to climate change (see e.g. Ziel and Bugmann, 2005). The hydrological regime of such environments is influenced strongly by water accumulation in the form of snow and ice and the corresponding melt processes. A modification of the present climate and especially of temperatures can, therefore, affect the hydrological regime (Horton *et al*., 2006) and cause important changes in the management of water, particularly on uses highly dependent on the hydrological regime, such as hydropower production. In Switzerland, hydropower provides about 75% of consumed electricity, of which around 60% is produced from storage reservoirs (Swiss Federal Office for Energy, 2003). Apart from the obvious economic interest in electricity production from water accumulated in reservoirs, hydropower plants have important socio-economic roles at different scales. In the Swiss Alps — at the very local scale — related infrastructures and employment opportunities encourage decentralised rural settlements, particularly if the accumulated water serves some secondary purpose such as irrigation. At a more regional scale, dams and reservoirs may protect areas downstream from flooding.

In Switzerland, the different stakeholders are becoming concerned about the potential impacts of climate change. While shareholders may welcome higher temperatures and induced melt, with consequent increased production of electricity and economic gain, the local population is more concerned about the security of the system.

Despite the importance of hydropower production and its potential sensitivity to climatic change, relatively few studies have addressed these issues. Most studies analyse only the direct effect of climate change on the water cycle rather than assess the impacts in terms of water management. Garr and Fitzharris (1994), Robinson (1997) and Westaway (2000) analysed the climatic sensitivity of accumulation power power plants and mixed power plants in terms of total annual production and consumption of hydroelectricity in New Zealand, in the eastern United States and in Switzerland respectively. Mimikou and Baltas (1997) assessed the reliability of a hydropower scheme in Greece under three different climate scenarios based on global circulation model (GCM) outputs. Harrison and Whittington (2002) analysed the financial and technical viability of hydropower projects for the Zambezi under climate change. Bergström *et al.* (2001) studied the climatic change impact on potential hydropower production in Sweden for plants as yet unplanned. They attempted to integrate the modelling uncertainty due to the choice of the GCM as well as the parameterisation of the evapo-transpiration (ET).

The present study aims at quantifying the climate change impacts on a water resource system and its management at the scale of a single hydropower plant at a daily time step in order to analyse everyday management situations — including extreme situations — rather than average electricity production. Payne *et al.* (2004) and Christensen *et al.* (2004) have carried out a comparable climate change impact analysis for hydropower production in large catchments in the western United States. They used three ensembles of a business-as-usual future climate scenario and two different downscaling methodologies for the impact analysis. Their results, therefore, cover only a small part of the potential climate change-induced system modifications. Another important limit is pointed out by Barnett *et al.* (2004) — a companion paper of the two case studies — who state the desirability of confidence limits rather than single estimates of climate change impacts.

The methodology used in the present study has been developed to answer these two major challenges in the field of climate change impact research: to cover a large range of potential climate change impacts and to quantify all related modelling uncertainties. The results obtained are, therefore, not central estimates of the expected system modifications but the entire range of possible changes with associated probabilities. Ultimately, these results should enable the answer to the following question: Given the modelling uncertainties, does climate change cause a statistically significant modification of the system performance?

The analysis presented does not address other potential modifications of the system studied such as modifications of the demand for electricity induced by climate change, population growth or the technological progress that can be assumed to have a considerable impact on the management of the system. The potential impact of climate change is analysed on the basis of the water resources system as it exists today.

Methodology: overview

The analysis of potential climate change impacts on the management of a water resources system requires setting up an integrated simulation tool to simulate the behaviour of the system for different climatic situations. In the context of hydropower production in a highly glacierised catchment, this simulation tool includes four types of models: a water management model, a hydrological model, a glacier surface evolution model and a model for the generation of local scale meteorological time series under a given climate change scenario. The first three model types, the required input data and the model calibration are discussed hereafter. In the present study context, a modelling time step of one day has been chosen as this enables a detailed analysis of the daily hydropower production performance. At the chosen spatial and temporal scale, the water routing through the hydraulic system can be assumed to be negligible. Consequently, the only part of the hydraulic system that is modelled is the lake reservoir, the storage evolution of which is modelled simply by the equation of continuity.

The future local scale meteorological time series — namely daily mean precipitation and temperature — are generated by perturbing the observed series for a control period according to the method of Shabalova *et al.* (2003). In this method, the perturbation of local scale precipitation and temperature is based on the corresponding regional scale outputs of a Regional Climate Model (RCM) for the same control and future period. As an example, the scaling equation for temperature is:

$$T_{scen,s}(t) = [T_{obs,s}(t) - \bar{T}_{obs,s}]*\sigma_{fut,s}/\sigma_{cont,s} + \bar{T}_{obs,s} + (\bar{T}_{fut,s} - \bar{T}_{cont,s}) \quad (1)$$

where $T_{scen,s}(t)$ (°C) is the local scale scenario temperature on day t of the season s (s = 1, 2, 3, 4), $T_{obs,s}(t)$ the corresponding observed temperature and $\bar{T}_{obs,s}$ the observed mean daily temperature of the season s. $\sigma_{fut,s}$ and $\sigma_{cont,s}$ are the seasonal standard deviations of the daily temperatures of the future and the control climate experiments and $\bar{T}_{fut,s} - \bar{T}_{obs,s}$ is the difference in mean daily temperature between these two experiments.

In the present study, the necessary RCM statistics for the times series perturbation are the result of the global-mean warming – regional climate - scaling methodology presented by Hingray *et al.* (2007a). Note that the future potential evapotranspiration (PET) has been interpolated as a function of the future temperature based on the observed relationship for the control climate, assuming that this relationship remains constant in the future.

The integrated simulation tool is used to simulate the system behaviour under the observed climate for the control period 1961–1990 and under the future climate scenarios for the period 2070–2099. A case study-specific indicator set is elaborated to evaluate the system performance and to compare the control and the future situation. The main objective of the present study is to quantify the associated modelling uncertainties. The potential sources of uncertainty are discussed and the most relevant ones included in an overall uncertainty analysis of climate change impacts based on Monte Carlo simulations .

The application of this general methodology is specific to a given modelling context. The case study used is presented first before discussing in further detail the climate change impact analysis and the integration of modelling uncertainties.

Case study: dam of Mauvoisin

SYSTEM DESCRIPTION

The dam and accumulation reservoir of Mauvoisin is located in the southern Swiss Alps (Fig. 1) as part of a hydropower plant owned and managed by Forces Motrices de Mauvoisin (FMM). The reservoir, filled initially in 1958, can store a total volume of 204 million m^3 of water, corresponding to 660 GWh and around 75% of the mean annual discharge from the hydrological catchment. Consequently, the hydropower production is highly flexible in time, the main economic interest for the managers being to shift the electricity production from summer when the hydrological inflow is high to winter when the electricity demand is high. The mean annual electricity production is about 1000 GWh, corresponding to 2.5% of the total Swiss hydropower production.

Table 1 gives the mean physiographic and meteorological characteristics of the natural and artificially connected catchment feeding the reservoir. The maximum daily water inflow is about 6×10^6 m^3 and the mean annual inflow 265×10^6 m^3. The hydrological regime is strongly influenced by glacier and snowmelt. It is of the so-called a-glacier type (Spreafico *et al.*, 1992): the maximum monthly discharge is in July and August and the minimum monthly discharge, in February and March, is about 100 times less.

Table 1. Main physiographic and meteorological characteristics of the case study catchment; the temperature corresponds to the mean catchment altitude, the precipitation to the area average value (reference year for glaciation is 1989, for hydro-meteorological data 1961–1990)

Characteristic	*Value*
Area (km^2)	169.3
Glaciation (%)	41.4
Mean slope (°)	26.7
Min. altitude (m a.s.l.)	1961
Mean altitude (m a.s.l.)	2940
Max. altitude (m a.s.l.)	4305
Mean annual precipitation (mm)	1530
Mean daily temperature (°C)	-3.6

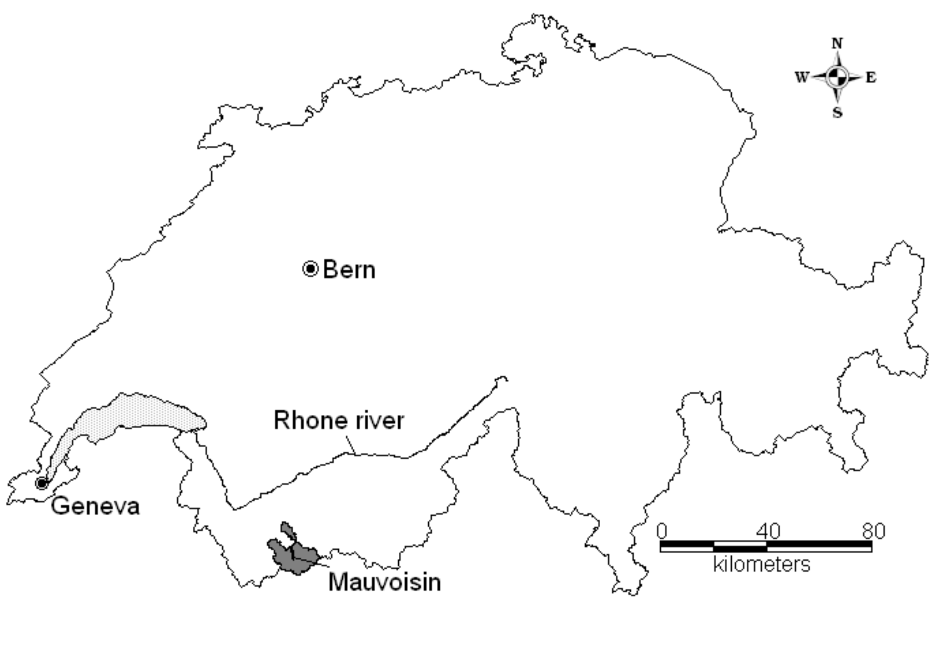

Fig. 1. *Location of the case study catchment in the Swiss Alps ©(SwissTopo, 1997)*

DATA COLLECTION

The hydrological and glacier surface evolution model needs three input time series, namely daily mean values of temperature, precipitation and potential evapotranspiration (PET). For the model calibration and validation and the control simulation of the system, precipitation and temperature time series were used from a meteorological station located within the catchment. The PET time series is calculated based on the Penman-Monteith version given by Burman and Pochop (1994). Daily mean inflow into the accumulation reservoir and electricity production data were obtained from FMM. Based on these data, the hydrological model was calibrated for the years 1995 to 1999 and validated for the years 1990 to 1994.

HYDROLOGICAL AND GLACIER SURFACE EVOLUTION MODEL

Model structure

The daily discharge simulation is carried out through a conceptual, semi-lumped model developed by the authors and presented in some detail by Schaefli *et al.* (2005). The model has two levels of discretisation; the first corresponds to the separation between the ice-covered part of the catchment (covered by glacier or isolated ice patches) and the non-ice-covered part and the second corresponds to a sub-division into elevation bands. The hydrological behaviour of each of the resulting spatial units is assumed to be homogeneous. The discharge simulation for each unit includes the following steps: interpolation of meteorological time series based on an altitudinal variation factor, separation of rain- and snowfall based on a threshold temperature, computation of snow accumulation and snow- and ice melt through a degree-day approach and transformation of rainfall and meltwater into runoff through a reservoir-based modelling approach. Figure 2 shows the hydrological model structure for a given spatial unit. The runoff transformation sub-model differs for ice-covered and non-ice-covered units. In the first case, two parallel linear reservoirs are used, one for snowmelt and rainfall and one for ice melt–runoff transformation. For non-ice-covered spatial units, snowmelt and rainfall–runoff transformation is carried out through two parallel reservoirs, a linear and a non-linear reservoir to simulate the slow and quick flow components of discharge.

This hydrological model has the following eight parameters to be calibrated: the altitudinal precipitation correction factor, the degree-day factors for snow- and ice melt, the linear reservoir outflow coefficients for the ice-covered spatial units and, for the non-ice-covered units, the maximum storage and outflow coefficients for the linear reservoir and the non-linear reservoir coefficient.

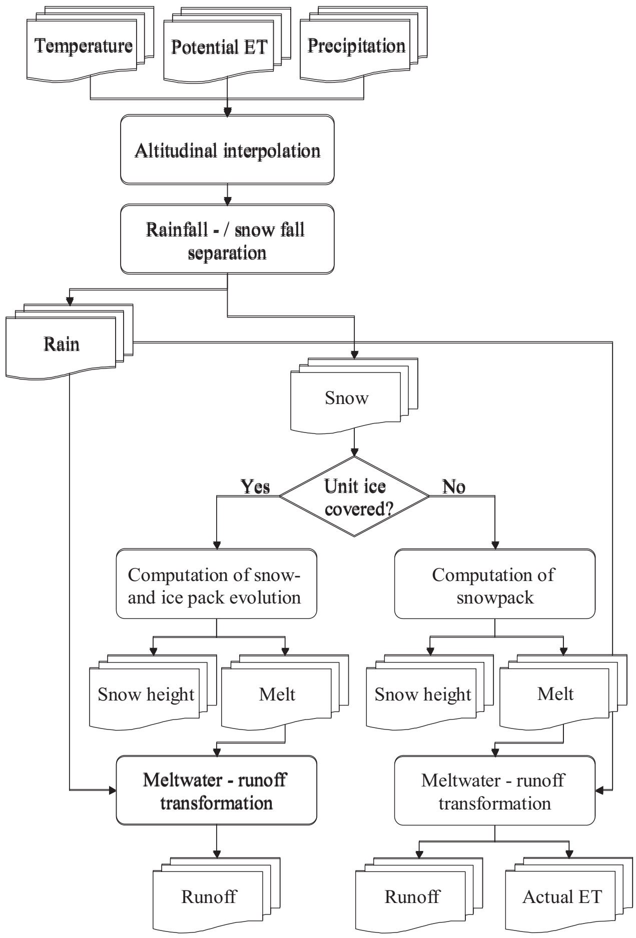

Fig. 2. *Hydrological model structure for one spatial unit*

The glacier surface is supposed to be constant for a given simulation period. For future scenario simulation, the ice-covered surface has to be updated. In the present study, this update is based on the so-called accumulation area ratio (AAR) (Anonymous, 1969). For a given hydrological year (starting on 1 October), this ratio can be computed from the sum of spatial units that experience snow accumulation (Schaefli *et al.*, 2005). Assuming that the mean inter-annual AAR is characteristic for a given glacier and remains constant for future periods, the glacier surface for future climatic conditions can be estimated according to Eqn. 2.

$$A_{glacier} = \frac{A_{acc}}{AAR_m} \tag{2}$$

where $A_{glacier}$ (km^2) is the total area of the glacier and A_{acc} (km^2) the simulated mean interannual accumulation area for the future climatic conditions. AAR_m is the mean inter-annual accumulation area ratio simulated for the control climatic conditions, for which the total ice-covered area is known.

For a further discussion of the glacier surface evolution model, refer to Schaefli (2005).

Hydrological model calibration

The hydrological model has been calibrated based on a Metropolis-Hastings algorithm according to the methodology presented by Kuczera and Parent (1998). The algorithm used is presented in Schaefli *et al.* (in press). This Markov Chain Monte Carlo (MCMC) methodology gives the posterior distribution of the model parameters and the associated modelling residuals that are supposed to be normally distributed. Consequently, modelling confidence intervals can be simulated for the daily discharge prediction by sampling the joint posterior parameter distribution. Figure 3 illustrates the 20% confidence interval of the daily discharge for one year of the model validation period. The model parameter set that corresponds to the maximum likelihood yields a Nash-value (Nash and Sutcliffe, 1970) of 0.88 and a bias of 2.5% for the calibration period. The corresponding values for the validation period are 0.87 and 1.0%.

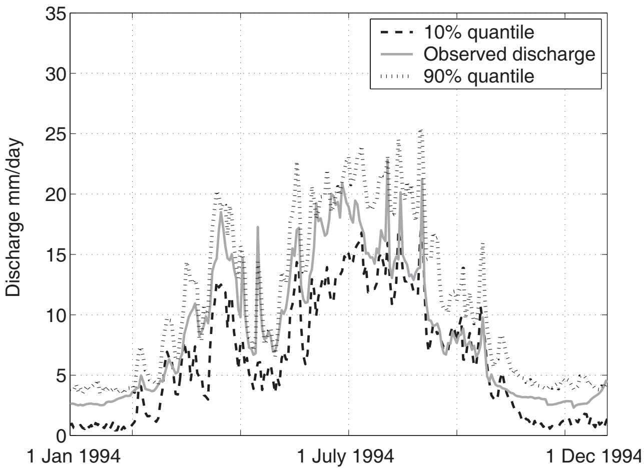

Fig. 3. *20% confidence interval for the daily discharge from the Mauvoisin catchment as simulated by the posterior model parameter distribution obtained through a Metropolis-Hastings algorithm*

Management model

The Mauvoisin hydropower plant comprises several power stations. There is no pump system for water recirculation. For the purpose of the present study, the interest is focused on the release management of the water accumulated in the dam and the corresponding main power station. Three turbines correspond to a maximum installed power of 127.5 MW and a maximum total discharge of 34.5 $m^3 s^{-1}$, the hydraulic head varies between 320 m and 490 m and the corresponding electricity production varies between 0.73 and 1.10 kWh per m^3 of water released through the turbines.

The dam belongs to a stock corporation composed of six shareholders. Each shareholder exploits its part of the accumulated energy according to its own strategy that is strongly influenced by the electricity demand but also by the annual water inflow into the lake. The dam manager monitors the changing lake level to ensure the safety of the hydropower plant and an optimal lake filling by the end of the snow and glacier melt season (around end of August).

The inflow can be reduced during critical situations by disconnecting some of the 12 water intakes. Such critical situations occur if the water level comes close to 97.7% of the maximal acceptable level. If the water level reaches the maximal acceptable level, an emergency management plan defines the actions to be undertaken that include water release through the spillway (up to 347 $m^3 s^{-1}$). The spillway has never yet been activated; if it were necessary to do so, its activation could lead to severe inundations downstream. The only other management constraint to be respected refers to the maximum discharge in the river that receives the water released through the turbines: Hydropower production has to be stopped if the discharge reaches 930 $m^3 s^{-1}$ in the Rhone river. There are no minimum discharge constraints that affect the hydropower management as the minimum discharge in the dammed river is ensured by a diverted spring.

These few considerations show that — except for extreme situations — there are no clearly defined management rules. The development of the lake level is dependent on the electricity production strategy of the different shareholders and is therefore strongly influenced by electricity demand and offer (available hydropower). A detailed analysis of historic release and inflow data showed, however, that the monthly release management is highly dependent on the hydrological regime whereas the release at smaller time steps is conditioned by other factors such as the strong weekly electricity demand cycle (the demand is much lower during weekends). Therefore, a mixed deterministic–stochastic model of the water release has been developed: The deterministic part models the mean seasonal release for winter and summer months and the stochastic part simulates the daily variations of the release that may be conditioned by the electricity market (Eqn. 3).

$$r_n = M_s \phi_j + \theta_{n,s,j} \tag{3}$$

where r_n is the release through the turbines on day n of the year, M_s the mean daily release during season s (s = 2 if n between 16 May and 31 August, s = 1 otherwise), ϕ_j a weighting factor to distribute electricity production between week- and weekend days (j = 1 if n is a weekday, 2 otherwise) and $\theta_{n,s,j}$ is the residual of day *n*, given season *s* and day type *j* modelled by a Log-Weibull distribution.

The simulated release r_n is called the planned release, the actual simulated release on a given day being dependent on the above-mentioned management constraints, the maximum possible daily release and on the lake level envelope curves. These curves correspond for each day to the highest and lowest lake level observed over the whole exploitation period of the dam. The manager and the shareholders use these curves to guide their daily release decisions and they reflect therefore the management experience gained in the past. They are integrated in the water release simulation tool as follows: Whenever the planned release causes the lake level to lie outside these envelope curves, the actual simulated release is adapted in consequence. Spillway activation is simulated according to the emergency plan of the dam.

The management model predicts well the observed daily water release and the lake level progression. Fig. 4 illustrates the simulated and the observed cumulated water release for one year (for further details, see Schaefli, 2005).

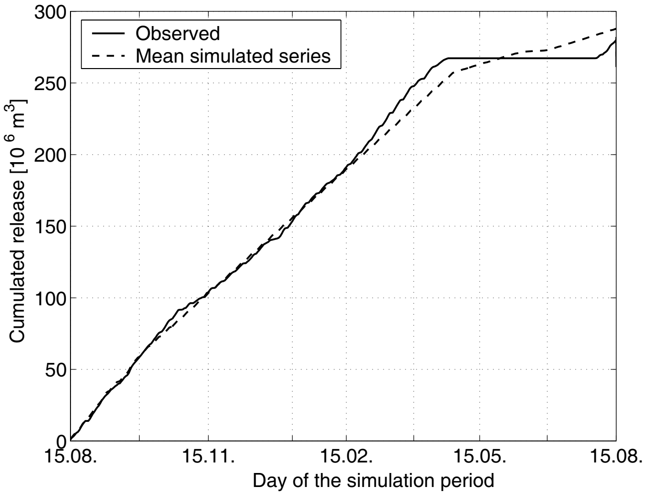

Fig. 4. *Simulated and observed cumulated daily release for the year 1995–1996*

Impact assessment: performance measurement

In the context of the present study, the climate change impacts on the management system are evaluated in terms of relative changes. A set of relevant indicators is used to compare the future scenarios with the control period. There are two types of indicators used: a set of quantitative criteria evaluating the total annual electricity production and its seasonal distribution. These indicators have been defined based on the management objectives stated by the manager and are system-specific. Additionally, more general qualitative indicators are used: the so-called RRV-criteria (Reliability, Resilience, Vulnerability), based on the methodology presented by Hashimoto *et al.* (1982). These RRV-criteria measure the number of failure periods, the speed of recovery from the failure states to satisfactory states and the importance of the occurring failure states. In the present application, the main interest is focused on electricity production and the failures states are therefore defined as follows: A failure state occurs if the actual daily release deviates more than 10% from the daily planned release. A day without failure state that follows a day with failure state is called a restoration state. The vulnerability of a failure state corresponds to the absolute deviation of the actual release from the planned release divided by the maximum possible release through the turbines. See Table 2 for a detailed description of all the indicators used and the corresponding measurement method. Note that there has never been any spillway activation or dam overtopping situation in the past.

Table 2. List of performance indicator names, signification and measurement method

I*ndicator name*	*Signification*	*Measurement method*
Reliability (%)	Frequency of failure states	(1 – sum of failure states) / total number of simulated time periods
Resilience (%)	Speed of recovery	Sum of restoration states / sum of failure states
Vulnerability (%)	Mean extent of failures	Sum of all daily vulnerabilities / number of failure states
Efficiency (%)	Water use efficiency	Sum of water released through the turbines / sum of water inflow into the reservoir over entire simulation period
Production (MWh)	Mean annual production	Sum of produced electricity/ number of simulated years
WinterProd (%)	Mean winter production	Sum of electricity produced during winter / total electricity production over the whole simulation period
Spill	Spillway activation index	Sum of days with spillway activation/ length of simulation period
Overtopping	Dam overtopping occurrence	Number of overtopping situations

Modelling uncertainties

Each of the modelling steps induces its specific modelling uncertainties. The different sources of uncertainty and their quantification are presented separately for each model type and illustrated based on one key output variable for each model type. All simulated probability density functions are the result of 10 000 random samples and corresponding simulations of the system behaviour.

Climate scenario and time series production

The temperature and precipitation time series are produced through the perturbation methodology presented by Shabalova *et al.* (2003). This methodology needs as input variables regional climate statistics expressed in terms of absolute or relative seasonal changes between the control and the future scenario climate model run. These statistics are the absolute change of seasonal mean temperature, the ratio of corresponding standard deviations, the ratio of seasonal mean daily precipitation and the ratio of corresponding coefficients of variation. The methodology presented by Hingray *et al.* (2007b) is used to sample the entire range of possible regional climate statistics under the global-mean warming probability distribution of Wigley and Raper (2001) and the scaling distribution of Hingray *et al.*, (2007a).

Figure 5 illustrates the resulting distribution of future mean monthly temperature and precipitation for the case study catchment, together with the mean monthly temperature and precipitation observed for the control period. Two sources of uncertainty are presented: the distribution induced by the scaling relationships under median global-mean warming (+2.6°C) and the distribution induced by the global-mean warming under median scaling relationships.

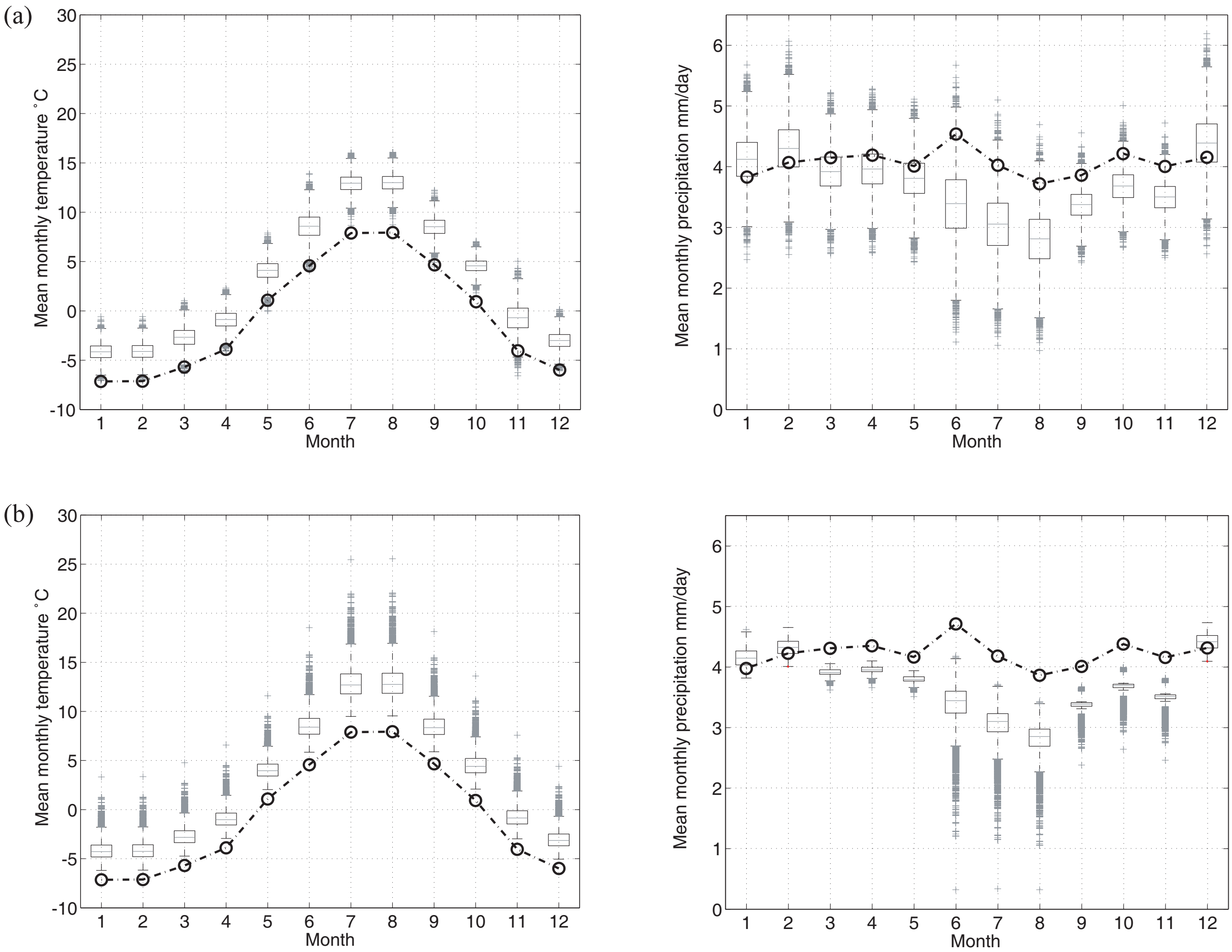

Fig. 5. *Boxplots of future mean monthly temperature and precipitation for the case study catchment, the black circles correspond to the mean monthly values for the control period; (a) induced by the regional scaling distribution given the median global-mean warming (+2.6 °C) and (b) induced by the global-mean warming distribution given median regional scaling relationships*

Under the median global-mean warming and the entire range of regional scaling uncertainty, the mean monthly temperatures of the control period correspond to outliers of the simulated future distributions. This means that even under a median global-mean warming scenario, the predicted temperature increase is significant for all months (Fig. 5a). Considering the entire range of global-mean warming, the mean monthly temperatures of the control period are strictly lower than the simulated future distributions (Fig. 5b). The simulated distributions of future mean monthly precipitation — both under median global-mean warming and under median regional scaling relationships — show a strong seasonality with less precipitation during summer months, whereas the current climate has only a slight seasonality with maximum precipitation during the month of June. The uncertainty induced by the global-mean warming on the simulated future mean monthly climate leads to 90% prediction intervals for the temperature of between 2.5°C (December) and 4.3°C (August) and to precipitation prediction intervals of between 0.2 mm day^{-1} (May) and 1.0 mm day^{-1} (June). The uncertainty induced by the scaling relationships on the predicted temperature is of the same order of magnitude (90% prediction intervals of between 2.4°C for October and 4.8°C for November) but considerably higher for precipitation (interval of between 0.8 mm day^{-1} for September and 1.9 mm day^{-1} for June).

The uncertainty induced by the climate scenario and meteorological time series production has a direct impact on the water inflow into the reservoir. Figure 6 presents the uncertainties induced separately by the global-mean warming respectively the scaling distribution on the mean annual inflow into the reservoir. The 90% prediction interval is slightly smaller for the uncertainty induced by the scaling relationships than for the uncertainty induced by global-mean warming (interval corresponding to 47*10^6 m^3 yr^{-1} respectively 54*10^6 m^3 yr^{-1}).

Hydrological modelling uncertainty

A Metropolis-Hasting algorithm has been used for the calibration of the hydrological model. The resulting joint distribution of the model parameters and the standard deviation of the residuals gives a good estimate of the uncertainty induced by the hydrological model (Schaefli *et al.*, in press; Schaefli, 2005). Figure 7 illustrates the hydrological modelling uncertainty induced on the mean monthly and the mean annual water inflow into the reservoir given the observed meteorological time series for the control period and given the median global-mean warming, the median scaling relationships and the median AAR-value for the future period.

The 90% prediction interval of the mean annual inflow is of the same order of magnitude for the control and the future period (7.8*10^{6}m^3 yr^{-1} and 7.2*10^6 m^3 yr^{-1}). Figure 7b shows that the increase of winter precipitation and corresponding snow accumulation, together with higher temperatures, leads to an earlier and stronger snowmelt peak in spring. For the median AAR-value considered, the median future ice cover of the catchment corresponds to 1.4% and the glacier melt is therefore small. The evapotranspiration increases due to the higher temperatures and the land-cover change (disappearance of the glaciers). The resulting hydrological regime is of the so-called nival type (maximum monthly discharge in June).

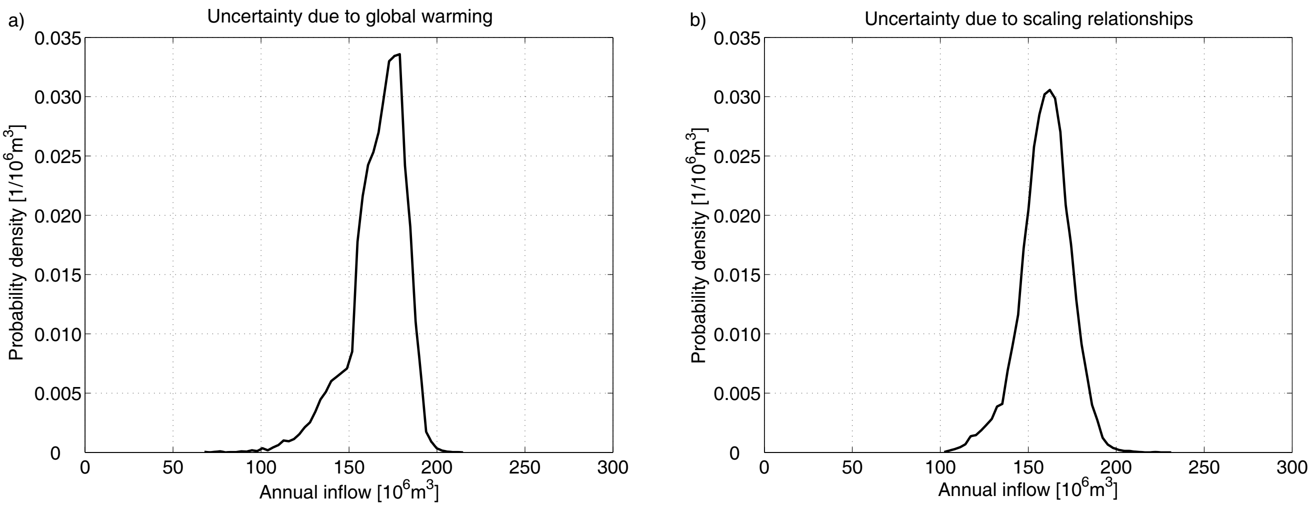

Fig. 6. *Probability density function of mean annual inflow into the lake: (a) induced by the regional scaling distribution given the median global-mean warming, the median AAR-value and the maximum likelihood hydrological parameter set; (b) induced by the global-mean warming distribution given the median regional scaling relationships, the median AAR-value and the maximum likelihood hydrological parameter set.*

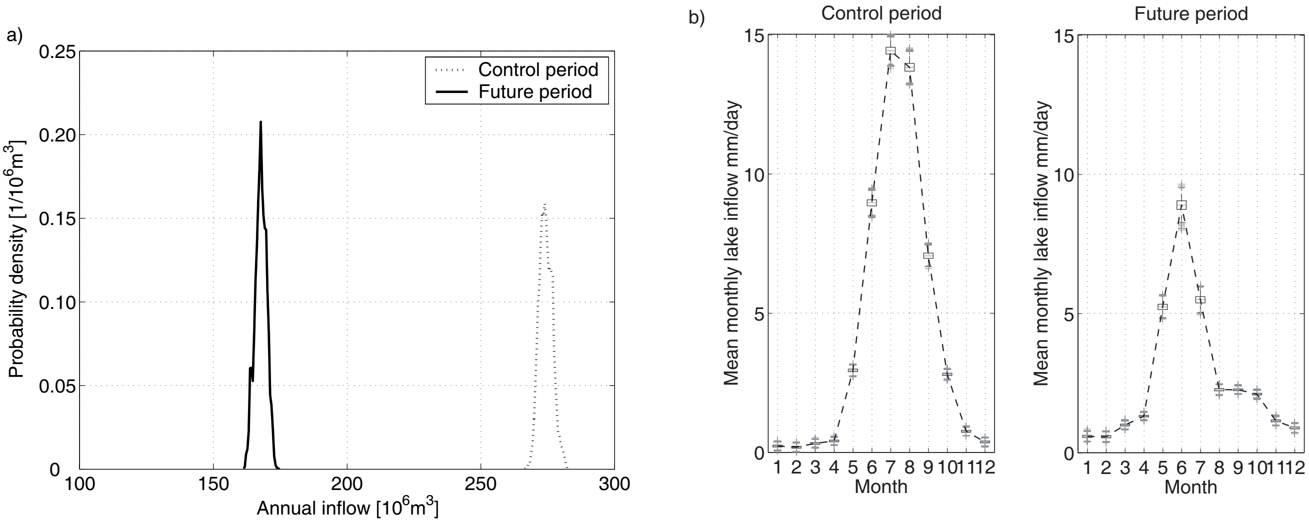

Fig. 7. *(a) probability density function of control and future mean annual inflow into the lake given the observed meteorological times series for the control period and the median global-mean warming, the median scaling relationships and the median AAR-value for the future period, (b) boxplots of corresponding mean monthly inflow.*

Glacier evolution uncertainty

The total ice-covered surface for a given simulation period represents *a priori* a considerable source of uncertainty. This uncertainty is due partly to the hydrological model parameters that condition the cycle of snow and ice accumulation and melt. Another important aspect is induced by the link between the simulated accumulation surface and the glacier surface evolution according to the glacier surface evolution model. Two main uncertainties arise: the extent of the ice-covered surface is uncertain, even for the model calibration period, as this surface varies from year to year and as the available data are infrequently updated. A much higher uncertainty is induced, however, by the assumption that the AAR_m remains constant in the future. A significant retreat of the glacier modifies for example its geometry, the amount of debris cover or the predominant exposition (and accordingly the balance of incoming radiation). The entire dynamic of ablation and accumulation processes could be modified.

Considering the chosen glacier surface evolution model, the last two types of uncertainty are easily integrated in the present modelling framework. The simulated annual AAR values for the calibration period can be modelled by a Log-Weibull distribution (Schaefli, 2005). Therefore, instead of using a fixed mean AAR value in Eqn. (2), the mean AAR value is drawn randomly for each simulation. The Log-Weibull distribution has been chosen because the distribution has to be limited to the interval [0, 1] and because the empirical frequencies of the AAR series are right-skewed. It is noteworthy that the higher the global-mean warming is, the smaller is the simulated accumulation area and the smaller is the effect of the chosen AAR_m on the total glacier surface. The influence of the AAR_m uncertainty disappears if the glacio-hydrological parameter does not simulate any accumulation (for a further discussion see also Schaefli, 2005).

Figure 8 illustrates the uncertainty induced by this random draw on the mean annual water inflow, given the median global-mean warming, the median scaling relationships and the maximum likelihood hydrological parameter set. The resulting 90% prediction interval of the mean annual inflow

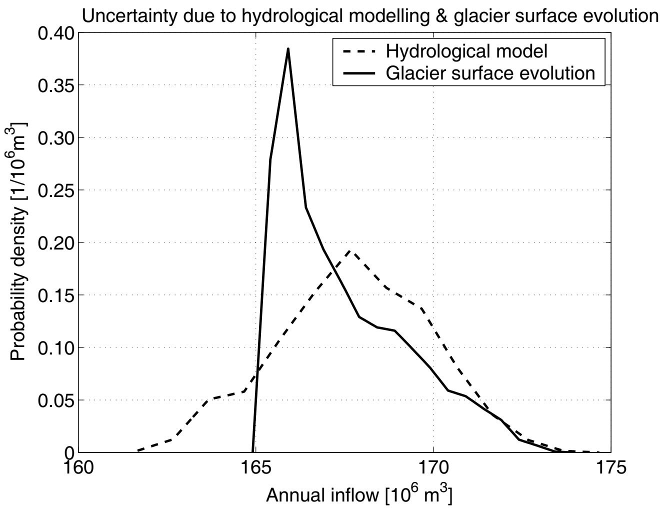

Fig. 8. *Probability density function of the mean annual water inflow under glacier surface evolution uncertainty (given the median global-mean warming, the median scaling relationships and the maximum likelihood hydrological parameter set) and under hydrological modelling uncertainty (given the median global-mean warming, the median scaling relationships and median AAR-value).*

($5.6*10^6$ m^3 yr^{-1}) is comparable to that resulting from the hydrological modelling (Fig. 8) but considerably smaller than those due to the generation of meteorological time series (see Fig. 6). This result is due to the fact that under the median future climate scenario, the remaining ice-covered area is small for the entire range of possible AAR-values (between 0% and 2.9% of the catchment area).

Another potential source of uncertainty is the reaction time of the glaciers, i.e. the time that elapses until a glacier reacts to a modification of the prevalent climate. According to Spreafico *et al.* (1992), the glaciers of the case study catchment have current reaction times of between a few years and a few decades. It is assumed however, that the gradual warming between the control and the future period will substantially reduce the corresponding ice volumes and surfaces, reducing therefore the reaction times significantly. Accordingly, it is assumed that the future modelling period of 30 years is long enough for the glaciers to react to the simulated climate.

Management modelling uncertainty

The most important source of uncertainty at this modelling level is the planned daily release through the turbines, the actual daily release being strongly influenced by the water cycle. The presented management simulation tool models the planned daily release by a Log-Weibull distribution. The distribution of all performance indicators is therefore easily obtained by multiple simulation of the system for a given hydrological parameter set, a given AAR-value and a given meteorological scenario. Figure 9 illustrates the distribution of the RRV values given the hydrological parameter set with the maximum of likelihood and given the observed meteorological times series for the control period and the median global-mean warming, the median scaling relationships and the median AAR-value for the future period.

The significant decrease in the reliability and the resilience and the increase in the vulnerability for the future period are due to the modification of the water cycle as illustrated

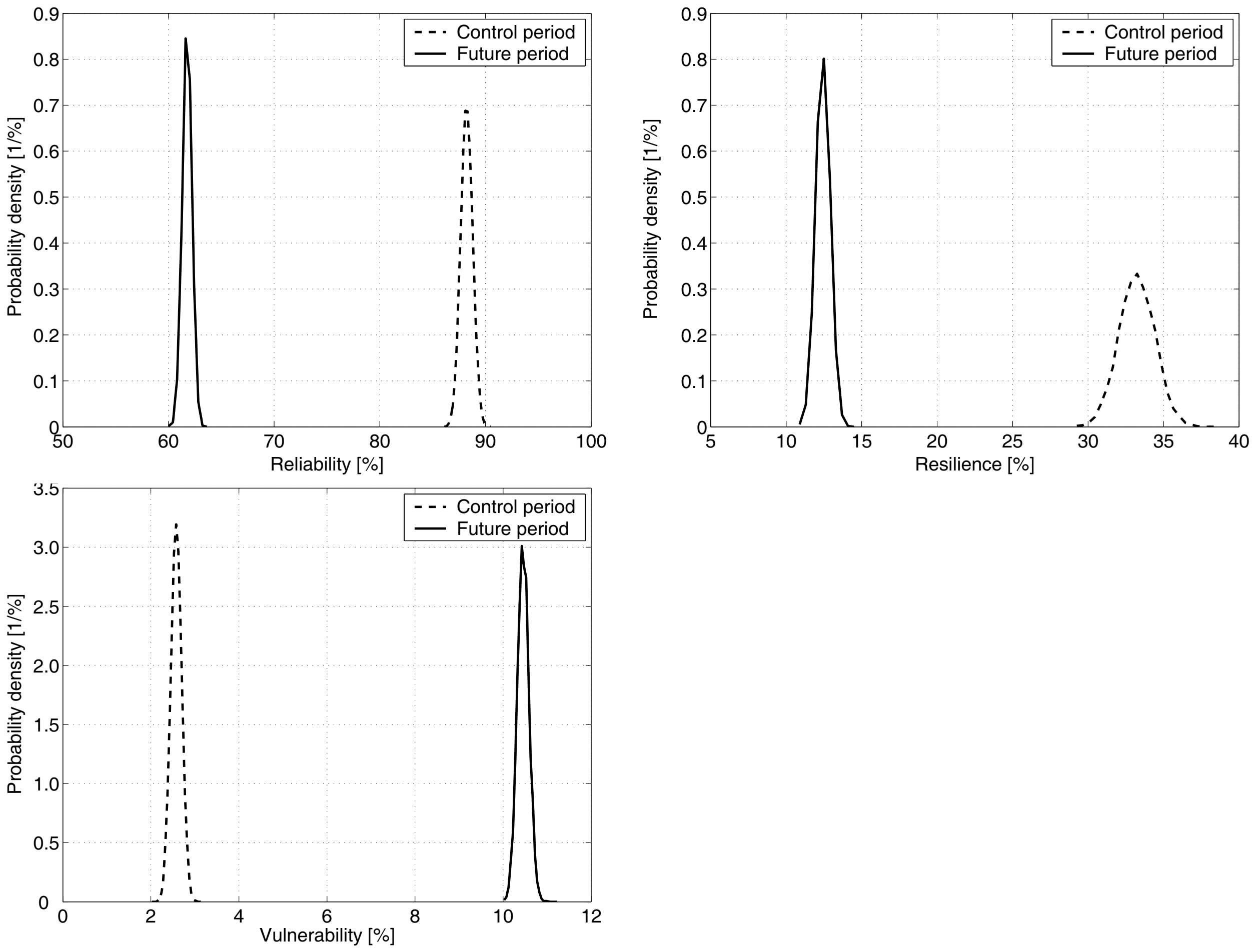

Fig. 9. *Distribution of the RRV values given the maximum likelihood hydrological parameter set and given the observed meteorological times series for the control period and the median global-mean warming, the median scaling relationships and the median AAR-value for the future period.*

in Fig. 7b (shift of the peak flow from summer to spring). Note the significant decrease of the 90% prediction interval for the resilience between the control (3.9%) and the future period (1.6%).

Integrated uncertainty analysis

The uncertainties inherent in each of the presented modelling levels can be combined by Monte Carlo simulations of the system behaviour, sampling randomly the appropriate parameters for each model type. The following five uncertainty levels are considered: (i) the daily release of the management model, (ii) the parameter estimation of the hydrological model, (iii) the AAR-value of the glacier surface evolution model, (iv) the scaling relationship between global-mean warming and regional statistics and (v) the global-mean warming. The previous section has illustrated the modelling uncertainty induced by each of them separately. Hereafter, the five uncertainty levels are successively combined in the above order. The corresponding probability density functions are the result of 20 000 random parameter samples and corresponding simulations of the system behaviour. A random parameter sample contains one randomly drawn parameter value for each parameter that is taken into account at a given level of uncertainty combination.

Figure 10 illustrates the shift and/or the flattening of the probability density function of the simulated management reliability when successively combining the first three uncertainty levels. Adding the hydrological parameter uncertainty to the daily release uncertainty shifts the function to the right and flattens it. Adding the uncertainty due to the AAR-value estimation enhances this effect. The influence of the different sources of uncertainty on the overall uncertainty depends on the considered performance criterion (Fig. 11). The most important part of the overall uncertainty is however introduced by the generation of the meteorological time series. Adding the scaling uncertainty to the three previous ones flattens the probability distribution function considerably for all performance criteria (Fig. 11). The global-mean warming enhances this flattening by lengthening the queues of the distribution. Table 3 illustrates the effect of successive combination of the five uncertainty levels based on the 5%, 50% and 95% quantiles of the mean annual electricity production. The global-mean warming covers a large part of the overall uncertainty: the 90% prediction interval for the overall uncertainty corresponds to 85.5 GWh, of which an interval corresponding to 32.3 GWh are induced by the global-mean warming uncertainty.

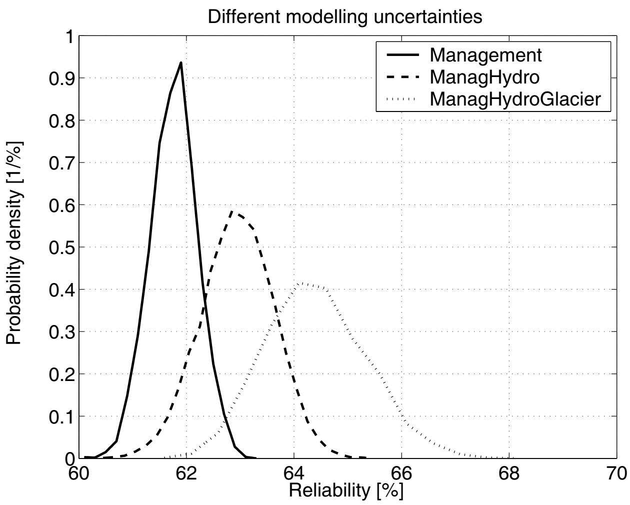

Fig. 10. *Probability density functions of the management reliability simulated by taking into account the release uncertainty (Management), the release and hydrological parameter uncertainty (Management & Hydro), the release, hydrological parameter and AAR-value uncertainty (Management, Hydro & Glacier).*

Table 3. 5%, 50% and 95% quantiles of the future mean annual electricity production (GWh) for increasing levels of uncertainty

Uncertainty level	*5%*	*50%*	*95%*
Management	146.8	147.0	147.2
Manag & Hydro	148.2	151.8	154.9
Manag, Hydro, Glacier	152.5	157.3	163.2
Manag, Hydro, Glacier, Scaling	128.0	155.1	181.1
All levels of uncertainty	102.7	158.5	188.2

Climate change impacts on the hydropower management

The probability distributions of the indicator values for the control and future periods are strictly different and the RRV values for the future period are worse than for the control situation. Tables 4 and 5 give the 5% and 95% confidence limits and the median of the simulated distributions of all the meteorological key variables and the indicators for the control and future periods. The distributions have been simulated given all related modelling uncertainties. For the future period, all identified modelling uncertainties are taken into account (i.e. those due to global-mean warming, to regional scaling relationships, to hydrological, glacier surface and management modelling), whereas for the control period, only the uncertainties due to the hydrological and the management model are included.

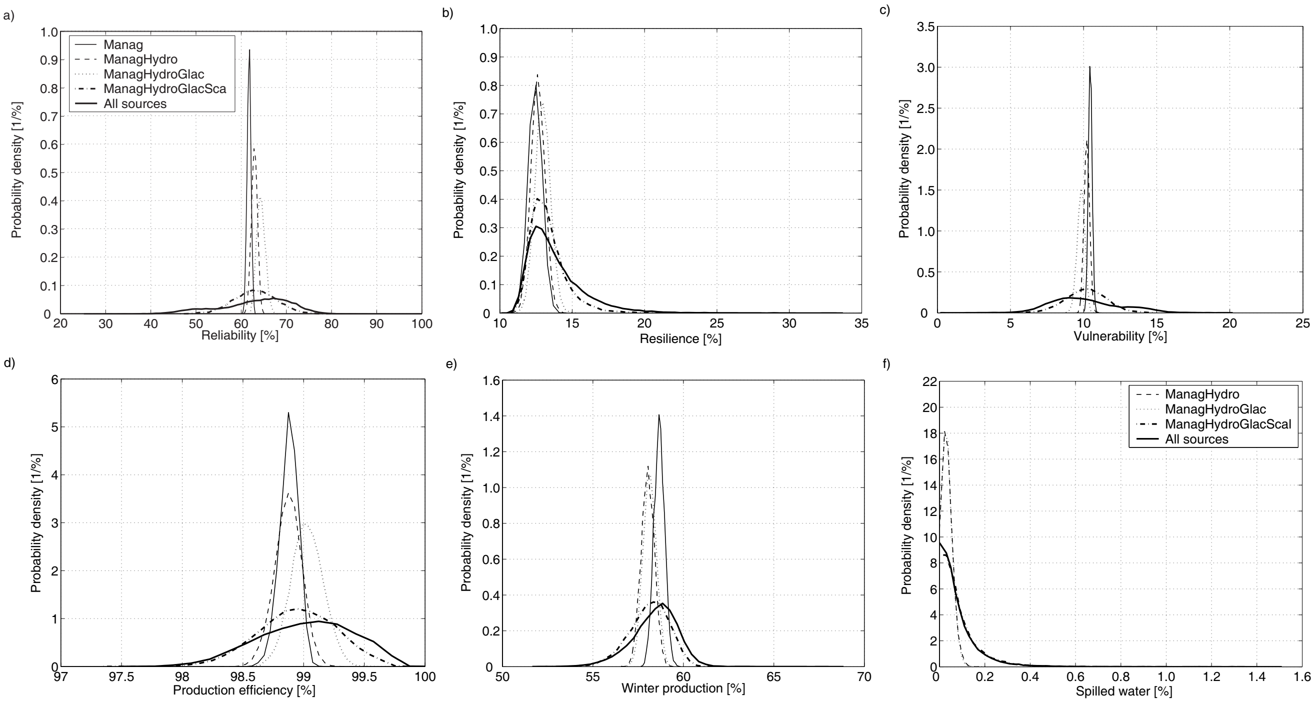

Fig. 11. *Evolution of the probability density functions of six performance criteria due to successive combination of 5 uncertainty levels: daily release (Manag), hydrological parameter estimation (Hydro), AAR-value (Glac), regional scaling relationships (Scal) and global-mean warming; for enhanced readability, the computed point frequencies have been removed; the criterion spilled water equals zero for the first level of uncertainty.*

Table 4. Median and 5 % and 95 % confidence limits of the distributions of mean daily temperature, mean annual precipitation, mean annual actual ET and glaciation for the control and future period, simulated given all related modelling uncertainties; the temperature corresponds to the mean catchment altitude, precipitation and actual ET are area average values; for the control period, there is no uncertainty for the temperature interpolation

	Control period			*Future period*		
Variable	*5%*	*50%*	*95%*	*5%*	*50%*	*95%*
Temperature (°C)-	-	–3.6	-	–1.8	–0.2	2.5
Precipitation (mm)	1500	1527	1551	1205	1411	1528
Actual ET (mm)	208	210	211	313	394	552
Glaciation (%)	-	41.4	-	0	1.4	6.9

The increase in the median value of the mean daily temperature corresponds to +3.4°C (Table 4). The minimum simulated mean daily temperature is equal to –2.9°C, the future temperature being therefore strictly higher than for the control period. The mean annual precipitation distributions for the control and the future period overlap slightly; the median value of the control period corresponds to 94.7% of the future distribution. The increase in simulated actual ET is considerable; the median future value corresponds to almost double the median value for the control period (Table 4). This result is due to the decrease in the glacier surface that augments considerably the catchment area contributing to the actual ET. The hydrological model does not account for evaporation over the ice-covered areas as in the overall water balance it is compensated by the ice melt estimation. Related to the ice-free catchment area, the median annual actual ET for the control period corresponds to 358 mm. This shows that the absolute increase between the simulated median value for the control and the future period is small.

Table 5. Median and 5 % and 95 % confidence limits of the indicator value distributions simulated given all modelling uncertainties for the control and future period.

	Control period			*Future period*		
Indicator name	5%	50%	95%	5%	50%	95%
Reliability (%)	87.3	88.2	89.2	47.3	64.2	74.3
Resilience (%)	31.3	33.2	35.2	11.7	13.3	17.7
Vulnerability (%)	2.4	2.6	2.8	6.8	9.9	14.4
Efficiency (%)	99.5	99.6	99.7	98.3	99.0	99.6
Production (GWh)	246.2	246.5	246.8	102.7	158.5	188.2
WinterProd (%)	62.7	63.0	63.4	56.1	58.6	60.2
Spill (%)	0.00	0.00	0.00	0.00	0.06	0.25
Overtopping	0.00	0.00	0.00	0.00	0.00	0.00

The increase in temperature over the whole year and the decrease in annual precipitation lead to an important reduction in the simulated ice-covered area and of the available water in the system. Compared to the median hydropower production for the control period, the median future production corresponds to a decrease of 36% (Table 5). The water use efficiency, however, remains more or less constant for the future period; the loss of hydropower production is exclusively due to the important decrease in available water through the decrease in precipitation and ice melt and the increase in evapotranspiration. The hydropower production undergoes a shift of about 7% from winter to summer production due to a modification of the prevalent hydrological regime. This regime modification explains partly the decrease in the release reliability, as planned releases during the winter months can no longer be met and production in summer months is sometimes higher than planned. There is a significant increase in the release vulnerability that measures the average difference between planned and actual release through the turbines: the control median value of 2.6% corresponds to around 70 MWh production difference between planned and actual production whereas the future median value of 9.9% corresponds to a production difference of around 269 MWh. This considerable worsening of the release vulnerability is accompanied by occasional spillway activation for the future period. The overall water loss through spillway activation is negligible even for extreme climate change scenarios (95% quantile corresponds to 0.25% (Table 5) and the highest simulated value to 1.3%). The corresponding water discharge, however, could potentially endanger the downstream area. The maximum simulated discharge through the spillway corresponds to 177.4 $m^3 s^{-1}$. A detailed risk analysis is beyond the context of the present study but the value can be compared to the maximum discharge recorded before the dam construction (45 years of data), some 59 $m^3 s^{-1}$ This shows that the simulated spillway discharge would represent a substantial new hazard. This discharge value has to be considered with care, however, for the following reasons: (i) contrary to reality, the management model does not include any meteorological forecast; (ii) this value corresponds to an extreme scenario. The maximum spillway activation simulated for the median global temperature increase (+2.6°C) and taking into account all other modelling uncertainties, corresponds to 60 $m^3 s^{-1}$ and equals the maximum discharge recorded before dam construction. A further analysis of the risk for the downstream inhabited areas is nevertheless recommended since the risk not only results from the potential hydrological hazard but also from a combination with the vulnerability of the system that may have increased considerably since the dam was built.

The above impact analysis on the performance of the hydropower system shows that the management system is able to deal with the entire range of predicted climate change. Under the given range of global-mean warming, the overall performance will decrease if the present management system is maintained unchanged, but the overall water use efficiency will remain stable and there will be no lasting damage to the entire hydropower system. The risk for downstream inhabited areas may, however, increase compared to the control period because of occasional spillway activations. In the context of climate change impact analysis, special attention should be paid to the sustainability evaluation of the studied systems. According to Loucks and Gladwell (1999), water resource systems can be called sustainable if they are able to satisfy the changing demands placed on them, now and into the future, without system degradations. The analysis presented cannot draw any conclusions about the system's ability to meet the electricity demand: its sustainability cannot therefore be judged.

Conclusions

A consistent methodology has been developed for analysing the impacts of of potential climate changes on a real-world water resources system and the results answer the main question motivating the present study; notwithstanding the modelling uncertainties, climate change causes a statistically significant modification of the system, the performance of which is affected. negatively

All results are conditioned by the underlying modelling assumptions and by the data used in long-term climate projections, namely the global-mean warming probability density function given by Wigley and Raper (2001) and the regional scaling relationships derived from 19 regional climate models according to the methodology of Hingray *et al.* (2007b). These two data sources incorporate the maximum amount of scientific knowledge currently available in the area of climate modelling. Whether or not these two data sets encompass the entire range of possible future climatic evolutions, they cover a sufficiently large range of potential climate evolutions to enable meaningful investigations of the system reaction to climate change. The most important conclusions of this study, independent of the exact form and of the exact mean value of the global-mean warming probability distribution, are: (i) at the temporal horizon considered, global-mean warming will have a negative impact on hydropower production; (ii) the regional climate response to a global-mean warming involves prediction uncertainties of the same order as the uncertainty in the global-mean warming itself.

The different modelling uncertainties included in the methodology have been chosen based on the following two criteria: the authors judged them to be important for the case study presented and necessary data and scientific knowledge exist to include them in the study. Some potentially important sources of modelling uncertainties not taken into consideration in the hydrological model include modifications of the evapotranspiration induced by land-cover change. Additional research into the generation of at site temporal time series based on regional climate statistics could potentially enlarge the overall modelling uncertainty. In particular, further work may reduce the potential loss of variability and extremes in this interface between the climate models and the hydrological model. The climate change impact analysis could also benefit greatly from further evaluation of the natural variability for the control period, for example based on an appropriate weather generator.

Another important modelling uncertainty issue arises from the conceptual hydrological model. Data scarcity in high mountainous catchments and the need for uncertainty estimation prevented the use of a physically-based model. In the area of climate change impact studies, however, the problem of extrapolation of a calibrated model beyond its domain of validation has to be confronted. This general problem could be approached by a model structure uncertainty analysis such as the one presented in Schaefli *et al.* (2004) and further developed in Schaefli (2005). Further research into how to include such structural uncertainties quantitatively in the presented climate change impact analysis has to be done.

The management system performance has been analysed for future climate situations assuming that all other elements of the system remain constant — a quite unrealistic assumption. Climate change induced modifications of the electricity demand could modify system management completely. Some authors have tried to analyse simultaneously the electricity demand and production (see e.g. Robinson, 1997; Westaway, 2000). The Swiss electricity market is, however, highly interconnected with the European one and a demand analysis is therefore far beyond the reach of the present study. It could nevertheless be interesting to complete the study by an analysis of different management adaptation strategies such as that presented by Payne *et al.* (2004). The management model used does not include any quantitative rainfall forecasts. As they become more and more precise, the realism of the management model could be enhanced by including short-term precipitation forecasts.

At the temporal prediction horizon (2070–2099) under consideration, the median decrease in hydropower production in the system corresponds to 36% compared with the control period. Given the highly non-linear relationships between the water availability, catchment glaciation, daily precipitation and temperature, it can be assumed that the decrease between the two periods is not linear. Because of the joint action of ice melt and evapotranspiration increase and precipitation decrease during intermediate periods, the climate change induced modification of water availability is presumably not even monotonous. The analysis of intermediate climate change scenarios would help to determine potentially critical situations due to a possible increase in water inflow into the reservoirs and would therefore complete the conclusions on climate change impacts on hydropower production in the Alps. However, further work focusing on in-between periods is conditioned on the availability of multiple climate change predictions, which is currently still problematic.

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